Plant accumulation of radioactive strontium with special reference to the strontium-calcium relationship as influenced by nitrogen. (Thesis)

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Publication date:
1973

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
Andersen, A. J. (1973). *Plant accumulation of radioactive strontium with special reference to the strontium-calcium relationship as influenced by nitrogen. (Thesis)*. Risø National Laboratory. Denmark. Forskningscenter Risoe. Risoe-R No. 278

[redacted]

Risø Report No. 278

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Danish Atomic Energy Commission

Research Establishment Risø

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January 1973

Sales distributors: Jul. Gjellerup, 87, Sølvgade, DK-1307 Copenhagen K, Denmark
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Denne afhandling er i forbindelse med de i forordet I - XI nævnte tidligere offentliggjorte arbejder af Den kgl. Veterinær- og Landbohøjskoles fagråd for landbrugsvidenskab antaget til offentligt at forsvares for den jordbrugsvidenskabelige doktorgrad.

København, den 1. februar 1973

J. Wismer-Pedersen

Formand for fagrådet for landbrugsvidenskab

Forsvaret finder sted fredag den 25. maj 1973 kl. 14 præcis i auditorium 3-03, Den kgl. Veterinær- og Landbohøjskole, Thorvaldsensvej 40.

ISBN 87 550 0177 7

CONTENTS

PREFACE

The present report summarizes and discusses a series of investigations on the plant uptake of radioactive strontium carried out during the last ten years. The main results of the experiments have been published in various articles and reports as listed below. These papers will be referred to by Roman numerals, while other literature will be given by author's name and publishing year and listed at the end of the review.

I Andersen, A. J., 1963. Influence of liming and mineral fertilization on plant uptake of radiostrontium from Danish soils. - Soil Science, 95: 52-59.

II Andersen, A. J., 1965. Uptake by plants of radiostrontium from contaminated soils. - Nature, 208: 195-196.

III Andersen, A. J., 1966. Reduction of the ^{90}Sr uptake by barley through high-temperature treatment and deep placement of the contaminated soil layer. - p. 421-427 in: Radioecological Concentration Processes, Pergamon Press, Oxford and New York, 1966.

IV Andersen, A. J., 1967. Investigations on the plant uptake of fission products from contaminated soils. I. Influence of plant species and soil types on the uptake of radioactive strontium and caesium. - Risø Report No. 170 pp. 32.

V Andersen, A. J., 1967. Investigations on the plant uptake of fission products from contaminated soils. II. The uptake of radioactive strontium placed at different depths in the soils. - Risø Report No. 174. pp. 19.

VI Andersen, A. J., G. Gissel Nielsen and G. Nielsen, 1967. Effects of fertilization on the strontium-calcium and caesium-potassium relationships in plants. I. The uptake and distribution of radioactive strontium and calcium in oats. - Royal Veterinary and Agricultural College, Denmark, Yearbook, 1967: 154-167.

VII Andersen, A. J., 1971. The uptake and distribution of strontium in oats as influenced by the time of supply. - Soil Science 111: 379-381.

VIII Andersen, A. J., 1971. Influence of phosphorus and nitrogen nutrition on uptake and distribution of strontium and calcium in oat plants. - Soil Sci. Soc. Am. Proc. 35: 108-111.

IX Andersen, A. J. and W. A. Jackson, 1972. Influence of nitrogen supply on uptake and transport of strontium and calcium in wheat seedlings. - Phys. Plantarum 26: 175-181.

X Andersen, A. J., 1972. Influence of nitrogen nutrition on the discrimination between strontium and calcium in oat plants. - Proceedings of FAO/IAEA Symposium on the Use of Isotopes and Radiation in Research on Soil-Plant Relationships including Applications in Forestry, Vienna 13-17 December 1971: 21-40.

XI Andersen, A. J., 1972. Effects of nitrogen nutrition on the uptake, distribution and chemical binding of strontium and calcium in oat plants. - Risø Report No. 256: 177-186.

1. INTRODUCTION

The occurrence and behaviour of strontium in the biosphere have acquired increasing interest since the advent of its long-lived radioactive isotopes which are products of nuclear fission. Small quantities of native strontium are widely distributed in soils, plants and animals, where its abundance is usually compared to that of the homologous element calcium. Considerable variation in the atomic ratio Sr/Ca has been found in parent rocks and minerals (Goldschmidt 1958). The ratio in the plant available exchangeable fraction of surface soils varies much less (Mitchell 1945), although appreciable differences between soils have been reported (Menzel and Heald 1959; Williams and David 1963). An analysis of some Danish soils showed that they contained from 500 to 1000 times as much calcium as strontium (Ref. IV), which corresponds very well with the above-mentioned reports from other parts of the world.

Radioactive isotopes of strontium are produced in large amounts by nuclear explosions, and strontium-90 is considered the most biologically hazardous of the fission products because it is readily transported through the food chain and, because of its long half-life (28 years), may become a long-term source of radioactivity in food.

The radiation hazard from food contaminated with radioactive fall-out is the internal radiation from fission products entering the bodies of animals and humans. The principal source of internal radiation immediately following a nuclear explosion is the external contamination of edible plants resulting from fresh fission products being deposited on agricultural areas. As time passes and the initially contaminated food has been discarded, the principal sources of internal radiation become indirect. From the contaminated soils the radioactive isotopes are absorbed through plant roots into food- and feedcrops. Radioactive strontium has been shown to be accumulated in above-ground parts of the plant, to a greater extent than any other of the long-lived fission products (Jacobson and Overstreet 1948; Gulyakin and Ydintseva 1957; Nishita, Romney and Larson 1961; Romney, Nishita, Olafson and Larson 1963), and numerous experiments have been carried out in order to evaluate in detail the various steps in the transport of radioactive strontium from the atmosphere through soil, plant and animal to the human organism. A comprehensive description of the problems involved has been edited by Dr. R. Scott Russell in: "Radioactivity and Human Diet", published by Pergamon Press 1966.

The present treatise summarizes investigations on the strontium accumulation in plants grown in soils which have been artificially contaminated with water-soluble radioactive strontium. Since the strontium-90 in radioactive fall-out has been shown to be largely water-soluble, the results from such experiments are assumed to be closely related to the conditions encountered in actual fall-out situations. The purpose of these investigations was to elucidate the consequences of a heavy contamination of agricultural areas with radioactive strontium and to evaluate the possibilities of influencing the amounts accumulating in crop plants.

The plant uptake of strontium is closely related to that of calcium and depends on the relative concentrations of the two cations adjacent to the root surface. Soil properties, which affect the relative availability of strontium and calcium, were evaluated for some typical Danish soils. The uptake of strontium can be influenced either by changing its actual concentration in the soil solution adjacent to plant roots or by changing the competition from calcium. Both possibilities have been tested. An effective reduction in strontium uptake was obtained by heating the contaminated soil layer and by deep ploughing. The availability was also effectively reduced by heavy applications of superphosphate. Whereas application of lime proved to be rather ineffective to reduce the uptake from most of the soils used. The uptakes by different plant species and varieties have been compared in pot experiments and the results revealed considerable variation in the strontium uptake.

Many investigations reported in the literature have been based on the assumption that strontium behaves like calcium in the soil-plant system, and it is generally recognized that the plant accumulation of the two elements occurs by quite similar processes. Several studies have, however, indicated that the relative uptake and transport of strontium and calcium may vary among plant species and be influenced by environmental growth conditions. It was shown in pot experiments (Ref. I) that nitrogen supply changed the relative distribution of strontium and calcium in oat plants. Since nitrogen is one of the most important growth factors in modern agriculture this was considered of great practical interest and it was therefore decided to elucidate these effects in more details. Attempts were made to evaluate how nitrogen addition affects the sequence of reactions which determines the strontium-calcium movement from the soil solid phase to the grain of oat plants.

2. EXPERIMENTAL METHODS

The uptake by plants of radioactive strontium was studied in different soil types collected from the ploughed layers of typical Danish agricultural areas. The content of stable strontium in these soils was found to be of the order of 1 to 2 micro-equivalent (μeq) per milli-equivalent (meq) of calcium. A similar ratio between stable strontium and calcium was used in the water culture experiments, whereas the radioisotopes were supplied in a 1:1 ratio in the uptake nutrient solutions. Deviations from this 1:1 ratio of radioisotopes in plant material were then taken as a measure of the extent to which the plants discriminated between strontium and calcium when they were grown in double labelled nutrient solutions.

2.1. Plant Culture

Three different types of plant culture technique were used.

Pot Experiments

Comparisons of uptake by different plant species and varieties and the influence of soil type and soil amendment were carried out as pot experiments in the greenhouse during winter or in the open during summer. The radioactive isotopes and plant nutrients were incorporated in the entire rooting zone in these experiments.

Field Experiments in Microplots

A similar technique as described by Frederiksson (1962) was used to investigate the effect of heat treatments, lime, phosphate fertilization and deep placement of the contaminated soil layer (Refs. III and V). This technique is convenient for studies of the long-term effects of the treatments.

Water Cultures

In order to study the accumulation of radioactive strontium in oats as influenced by the time of supply (Ref. VII), a technique was used which allowed the plants to be grown from seedlings to maturity without too frequent renewals of solutions (0.8 - 1.0 litre per plant). Studies on uptake and transport of strontium and calcium in seedlings were carried out as short time experiments and required less solution per plant (Refs. IX and X).

2.2. Analytical Procedures

Radioactivity in plant samples as well as in soil and plant extracts was determined by use of standard procedures. The γ-activity was measured with a well-type scintillation crystal and the β-activity was detected either with an end-window flowcounter or by liquid scintillation counting in Triton-Toluene counting solution. Appropriate corrections for self-absorption and activity decay were made.

Soil Analyses

The reported chemical and physical characteristics of the soils were determined by use of official methods and performed by The Laboratory of the Danish Heath Society. The extent to which added radioactive strontium and calcium equilibrated with stable calcium in the soils was measured in saturation extracts. The extracts were obtained by wetting 200 g of the labelled soil to saturation, allowing 48 hours for equilibration between added radioisotopes and native calcium. The wet soil was then transferred to a buchner funnel and the saturation extract collected by suction.

The relationship between the $^{85}Sr/^{45}Ca$ ratio in the solid phase to that in the solution phase is referred to as the selectivity coefficient, K_c, and is defined by Khasawneh, Juo and Barber (1968):

$$K_c = \frac{^{85}\mathrm{Sr}/^{45}\mathrm{Ca\ in\ solid}}{^{85}\mathrm{Sr}/^{45}\mathrm{Ca\ in\ solution}} = \frac{^{85}\mathrm{Sr\text{-}solid} \cdot {}^{45}\mathrm{Ca\text{-}solution}}{^{45}\mathrm{Ca\text{-}solid} \cdot {}^{85}\mathrm{Sr\text{-}solution}} ,$$

where ^{85}Sr-solid and ^{45}Ca-solid are obtained as the difference between the added activity and that remaining in the solution after equilibration. If the soil adsorbs strontium-85 preferentially to calcium-45, the K_c value will be greater than one.

Plant Analyses

Chemical analyses of plant materials were carried out on ash solutions by use of standard procedures.

The chemical binding of strontium and calcium in plants was studied (Ref. XI) by use of a procedure similar to that described by Schilling (1960). One gramme of plant powder was successively extracted with water, 0.5$\underline{N}$ $NaNO_3$, and 1.0$\underline{N}$ acetic acid. The β-radioactivity in these fractions was determined on evaporated aliquots of the solutions. Corrections for self-absorption were made.

2. 3. Terminology

The transport of radioactive strontium in biological systems is usually related to that of calcium, and th. differential behaviour of the two elements is conveniently described by the strontium-calcium observed ratio (OR) as proposed by Comar, Russell and Wasserman (1957); e. g. the $OR_{soil-plant}$ is defined as:

$$OR_{soil-plant} = \frac{Sr/Ca \text{ in plant}}{Sr/Ca \text{ in soil}} = \frac{Sr \text{ in plant} \cdot Ca \text{ in soil}}{Ca \text{ in plant} \cdot Sr \text{ in soil}},$$

where Sr/Ca in soils is the ratio of quantities available to the plants. To denote intermediary steps or specific physiological processes, the distribution or discrimination factor (DF) has been used, e. g.

$$DF_{straw-grain} = \frac{Sr/Ca \text{ in grain}}{Sr/Ca \text{ in straw}} = \frac{Sr \text{ in grain} \cdot Ca \text{ in straw}}{Ca \text{ in grain} \cdot Sr \text{ in straw}}.$$

It may be noted that the selectivity coefficient for strontium and calcium in the soil/soil solution system as mentioned above is in fact a distribution factor similar to the DF values.

3. FACTORS AFFECTING THE ACCUMULATION OF RADIOACTIVE STRONTIUM BY PLANTS

Plants absorb strontium as the divalent cation from the soil solution. Direct exchange between soil surface and plant roots has been suggested (Gonzales and Jenny 1958) but is presumably not important under normal growing conditions. The quantity of an element accumulated by plants is proportional to the external supply, provided the ionic concentration in the nutrient solution is sufficiently low (Russell 1966). Since radioactive strontium is always present at low ionic concentration, the uptake may be expected to be proportional to its concentration unless it is controlled by the presence of stable strontium or influenced by other cations present in the nutrient medium. It is well known that the chemical and biochemical behaviour of radioactive strontium and stable strontium is identical, and consequently the accumulation by plants of radioactive strontium may be affected by the presence of stable strontium in the soil solution.

The accumulation of strontium is also greatly influenced by the presence of calcium and much experimental work has been concerned with various factors affecting the ratio in which radioactive strontium and calcium are accumulated by plants grown in contaminated soil. Since the strontium-calcium relationship is to be discussed in more detail in subsequent chapters it may suffice to mention here the generally recognized similarity in behaviour of the two elements.

3.1. Influence of Soil Properties

The influence of soil properties on the uptake of radioactive strontium by plants has been the subject of many investigations reported during recent years (Menzel and Heald 1959; Evans and Dekker 1962; Scheffer and Ludwieg 1961; Schröder and Günther 1967; Frederiksson and Eriksson 1966). The uptake from 20 soils collected from different parts of Denmark varied almost by a factor of ten (Refs. I and IV). In general the highest uptake occurs from acid sandy soils with a low content of organic matter and the lowest uptake is found from heavy clay soil with a high degree of base saturation, but several factors may modify this general picture.

When water soluble radioactive strontium is added to the soil-solid: soil-solution system, the major part of it will be retained by the soil particles in an exchangeable or water soluble form (Schulz, Overstreet and Babcock 1958), while a minor part may be fixed in a non-exchangeable form. The amount present in either form depends on the length of time the radioactive strontium has been in contact with the soil (Squire 1960; Schulz and Riedel 1961), on the kind of exchange sites on the soil particles and on soil pH (Nishita, Kowalewsky, Steen and Larson 1956; Juo and Barber 1970). The radioactive strontium present in non-exchangeable form can be considered as non-available for uptake by plants (Robert and Menzel 1961). Thus the plant-available strontium in soil consists of the content in the soil solution and the amount held in readily exchangeable form on the surface of soil particles.

The relative uptake of radioactive strontium and calcium from contaminated soil depends on the relative concentration of the two elements in the soil solution adjacent to the root surface. This, in turn, is determined by the properties of the soil solid phase. Russell, Schoffield and Newbould (1958) determined the relative extent to which five different soil types adsorbed radioactive strontium and calcium from $CaCl_2$-solutions and their results showed a preferential adsorption of strontium for calcium. This was only slightly affected by the concentration of the $CaCl_2$-solution used, but greatly influenced by the soil type.

The soil properties affecting the relative distribution of strontium and calcium in the soil-solid:soil-solution system have been extensively elucidated by Khasawneh, Juo and Barber (1968) and the exchange selectivity of soils, clays and humic acid has recently been discussed by Juo and Barber (1969). The selectivity coefficient, K_c, of 63 soils varied between 0.61 and 1.51. The dominating factors influencing K_c were the content and kind of clay and organic matter. The mineral fraction adsorbed strontium preferentially to calcium, whereas the K_c for humate and a muck soil was less than one indicating a preferential adsorption of calcium for strontium on the organic exchange complex. When the Sr/Ca ratio in the equilibrating system was decreased the relative adsorption of strontium for calcium increased, indicating that the affinity for binding strontium varied with the relative concentration of the two ions. Nishita and Taylor (1964) have also reported evidence of variation in relative affinity of strontium and calcium in clay, minerals and soils.

The selectivity coefficients of the soils used in the pot experiments reported in Refs. I and IV varied between 1.13 and 1.52 with the lowest values in the muck soil from Lammefjorden, which was also to be expected according to results reported by Barber and co-workers. A close correlation ($r = 0.941$) was found between the Sr/Ca ratio in water extracts (soil:water, 1:5) and that in rye-grass in these soils (Fig. 1). A very acid and Ca-deficient soil, no. 29, was not included in this comparison because it was found that the Ca content in this soil was too low for accurate determination.

The rate of cation exchange between the soil solid phase and the extracting solution is normally fast, and equilibrium between added strontium and soil calcium is attained within few hours. However, slowly exchangeable fractions have been found in some soils (Taylor 1969) and it is possible that the exchange processes proceed slowly when the system is relatively dry as is normally the case in pot experiments. It was noted (Ref. I) that the Sr/Ca ratio in rye-grass decreased with time. This may be of importance for the interpretation of data on the distribution of strontium and calcium in other plant species grown in pot experiments with soil recently contaminated with radioactive strontium (Refs. VII and VIII).

3.2. Effects of Soil Management

Several attempts have been made to develop techniques to be used in emergency situations for reducing the plant uptake of radioactive strontium,

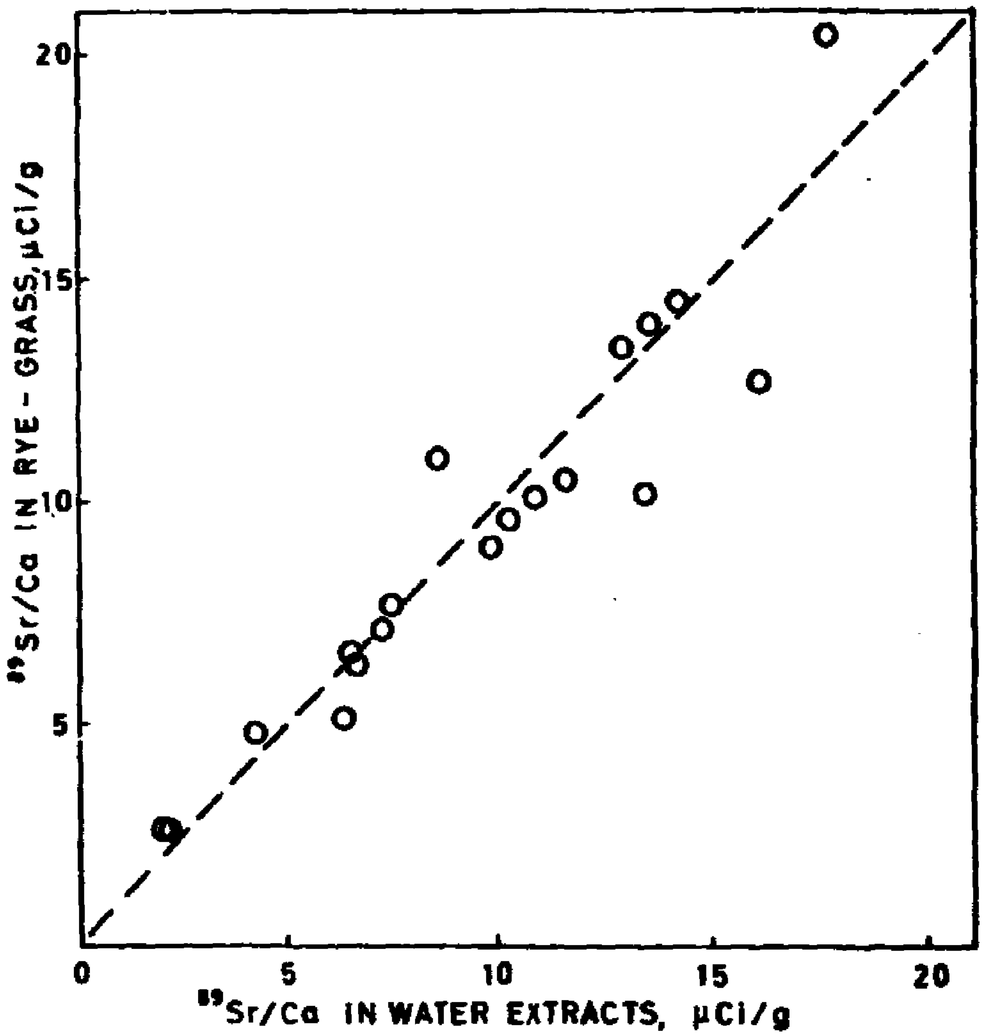


Figure 1. The relationship between the ^{89}Sr/Ca ratio in the first crop of rye-grass (Ref. IV), and the ratio in water extracts of the soils (soil:water, 1:5).

Different methods of removing the contaminated surface soil have been investigated and almost complete decontamination could be accomplished by removing the upper few cm soil (Menzel 1962) or by spraying the contaminated surface with an asphalt emulsion, allowing it to harden, and removing the crust that is formed. Heating the contaminated soil to 800-1000^{0}C was found to reduce the extractability and plant availability of radioactive strontium very effectively (Gregers-Hansen 1964 and Ref. II). Application of root inhibiting chemicals followed by deep placement was found by Menzel, Eck and Champion (1967) to be effective in reducing the radioactive strontium uptake by plants. However, such drastic remedial measures are not likely to be applicable on a large scale, and more attention should be focused on the possibility of influencing the uptake by normal agricultural practices.

The effects of deep ploughing on plant uptake of radioactive strontium have been elucidated in several experiments. The microplot experiment reported in Ref. V showed little change in uptake when the radioactive strontium was placed deeper than about 50 cm (Expt. I). Similar results were obtained by Schulz, Møberg and Overstreet (1959) from a lysimeter experiment with barley. Frederiksson, Haak and Eriksson (1969) simulated different tillage operations in microplot experiments and found that the deeper the radioactive strontium was placed the lower was the uptake by plants, though the effect was modified by a number of soil conditions and climatic factors. Myhre, Menzel, Roberts et al. (1964), Frere, Menzel, Roberts, Myhre et al. (1967) and Menzel, Eck, James and Wilkins (1968) reported extensive studies at various localities in the USA on the effects of ploughing to about 50 cm depth compared to conventional ploughing to about 15 cm. Deep ploughing reduced the accumulation of radioactive strontium in corn and soybean by 60% at most and that of oats and wheat-grain by about 20%, but there was much variability among locations and crops. In England, ploughing of contaminated fields to the depth of 30 cm and re-seeding with shallow-rooted crops caused the ratio between radioactive strontium and calcium to be less than 30% of that observed when the radioactivity was left on the surface (Milbourn, Ellis and Russell 1959; Milbourn 1960).

The long-term effects of deep ploughing can be evaluated from table 1, which summarizes seven years results from experiment II, Ref. V. In treatments A and B the strontium-90 was mixed into the upper 10 and 25 cm soil, while in treatments C and D the strontium-90 solution was sprayed upon the soil at depths of 25 and 45 cm, respectively. The soils were obtained from the State Experimental Stations at Blangstedgård (II), Ødum (III), St. Jyndevad (IV) and Borris (V).

The results showed considerable variations between soil types and the deep placement seems to reduce the uptake by rye-grass more than that of barley. The uptake was only slightly reduced when the strontium-90 was mixed into the entire plough-layer (B) as compared to the uptake from the upper 10 cm (A). An effective reduction was obtained when the contaminated soil is placed below the plough-layer and the effects persisted throughout the seven-year experimental period. Analysis of the soil profiles showed that the radioactive strontium could be recovered within few cm from the site of placement seven years before.

Table 1

The effects of placement on the average concentrations of strontium-90 in barley and rye-grass from experiments with four soils in microplots. Data given as nCi strontium-90 per g of dry matter (0.5 mCi strontium-90 per m^2 added 1964)

Soil Nos. 1)	Treatments	Barley, 1964-1966		Rye-grass			
		Grain	Straw	1967	1968	1969	1970
II	A, 0-10 cm	0.22	1.52	2.31	2.68	3.26	3.19
(s.c.l.)	B, 0-25 cm	0.15	1.10	1.55	1.73	2.06	2.19
	C, 25 cm	0.08	0.71	0.57	0.64	0.91	0.76
	D, 45 cm	0.06	0.48	0.31	0.23	0.35	0.35
III	A, 0-10 cm	0.38	2.44	4.29	3.32	4.44	3.67
(s.c.l.)	B, 0-25 cm	0.31	2.19	2.08	2.40	2.77	2.41
	C, 25 cm	0.28	1.97	1.12	1.03	1.60	1.73
	D, 45 cm	0.10	0.92	0.70	0.46	1.03	0.62
IV	A, 0-10 cm	0.36	2.65	6.19	5.50	5.46	5.17
(l.c.s.)	B, 0-25 cm	0.30	2.27	3.47	3.90	4.00	4.86
	C, 25 cm	0.18	1.90	1.72	2.29	2.71	2.83
	D, 45 cm	0.18	1.85	0.67	0.50	0.70	0.34
V	A, 0-10 cm	0.38	2.70	6.40	4.87	5.76	4.99
(l.s.)	B, 0-25 cm	0.28	1.99	3.22	3.33	4.04	4.00
	C, 25 cm	0.23	1.99	1.75	1.78	3.01	2.24
	D, 45 cm	0.16	1.25	1.22	0.91	1.38	1.28

1) s.c.l. = sandy clay loam; l.c.s. = loamy coarse sand; l.s. = loamy sand.

3.3. Effects of Stable Strontium and Calcium

When plants are grown in a nutrient solution containing radioactive strontium, added stable strontium and calcium will compete with radioactive strontium and usually reduce the uptake. In the soil-plant system the situation is much more complex, and the addition of small amounts of stable strontium or calcium may even increase the uptake of radioactive strontium (Romney, Alexander, Le Roy and Larson 1959; Romney, Alexander, Nishita and Larson 1961) because the initial small quantities of radioactive strontium are firmly adsorbed on the surface of soil particles but displaced by addition of the stable isotope or calcium. The amount of stable strontium required to reduce the uptake of radioactive strontium effectively was equivalent to more than 10 tons strontium/ha. Such a large amount may probably cause toxic effects on plants and would certainly be too expensive to apply on a large scale. Addition of calcium may increase the uptake of radioactive strontium from contaminated soils, but the Sr/Ca ratio in the crops, which are of primary interest in dietary considerations, is usually decreased.

The effects of liming contaminated soils have been studied in many countries in order to evaluate its effects on uptake of radioactive strontium by crops. Extensive field studies were reported by Milbourn (1960), Ellis, Mercer and Milbourn (1968), Frere, Menzel and Roberts et al. (1967) and Frederiksson, Haak and Eriksson (1969) and results from pot experiments have been reported by Frederiksson, Eriksson et al. (1958), Steenberg and Semb (1964), Evans and Dekker (1962) and Reissig and Fiedler (1966). The general conclusion from these and our own investigations (Ref. I) is that liming may reduce the plant uptake of radioactive strontium by a factor of 3 to 4 from acid soils but the effects are small and often insignificant on neutral or alkaline soils (table 3).

The effects of liming may partially be caused by a reduction of the concentration of hydrogen ions, which compete with strontium and other cations for exchange sites on the soil colloids. The hydrogen ion activity is decreased by liming and the hydrogen-strontium competition is changed to a competition with calcium which is not as effective as hydrogen in replacing strontium from the exchange complex. Furthermore, sparingly soluble compounds (carbonates, phosphates and sulphates) may be formed at neutral or alkaline reactions and precipitate more strontium than calcium.

3.4. Effects of Fertilization

Fertilization of contaminated areas may effect the plant uptake of radioactive strontium in various ways (Menzel 1958; Reitemeier and Menzel 1960). Materials containing calcium may have a similar effect as liming, and other cations added in fertilizers may compete with strontium for exchange sites both on soil particles and on root surfaces at the initial stages of uptake. Anions may facilitate the uptake of strontium and other cations as was demonstrated by Jackson and Williams (1968) for nitrate or the availability of strontium and calcium may be decreased owing to formation of slightly soluble compounds of phosphates, sulphates or carbonates.

Application of fertilizers containing nitrogen has been shown (Refs. I, VI, VIII and IX) to increase the accumulation of both strontium and calcium in cereal crops to a high degree. However, the two ions seem to be differently affected by nitrogen especially regarding distribution pattern in cereals. This nitrogen dependent discrimination has been extensively studied in oats and will be further discussed in chapter 5.

Somewhat contradicting results have been reported on the effect of potassium. Libby (1958) observed a 40% decrease in strontium uptake by radish when applying potassium sulphate, while Lee (1961 and 1962) did not obtain any reduction of radioactive strontium content in Thatcher wheat but the content in alfalfa was decreased by adding potassium chloride. Wiklander (1964) found that application of potassium decreased the strontium uptake in red clover more than that in barley and wheat. Evans and Dekker (1963) reported that potassium in their experiments generally decreased the uptake both of strontium and calcium, and potassium carbonate seemed to be more effective than potassium chloride. Although potassium may decrease the uptake of radioactive strontium and calcium it will probably not change the Sr/Ca ratio in the plant (Reissig and Fiedler 1966) to any great extent, as also indicated in the experiments reported in Refs. I and VI.

Application of superphosphate which contains appreciable amounts of calcium may have a similar effect as the equivalent amount of calcium in lime. Besides, it is possible that radioactive strontium will be precipitated as slightly soluble phosphates if sufficient amounts of water-soluble phosphates are added in such a way that a high concentration of phosphate is obtained in close contact with the radioactive strontium (Ref. VIII). The influence of concentrations was evaluated in a pot experiment where different methods of applying phosphate and radioactive strontium were compared. The importance of a close contact between added phosphate and the contaminated portion of the soil is clearly demonstrated by the results shown in table 2. When the radioactive strontium and a moderate amount of phosphate (3 g superphosphate/2 kg soil) were mixed into the entire rooting zone, almost no effect was noted. From the sandy clay loams the uptake even tended to increase. If a closer contact was obtained supply of phosphate reduced the concentration of radiostrontium in the rye-grass very effectively.

Table 2

Influence of phosphate on uptake of radioactive strontium by rye-grass grown in a pot experiment. Comparison of different methods (a - d) of applying the radioisotopes and phosphate.
Data given as nCi strontium-89 per g of dry matter

Soil type	mg P/pot	Methods of application 1)				
		a	b	c	d	S.E.
Sandy clay loam	0	6.53	6.45	6.35	6.35	±0.42
	250	8.42	5.68	4.41	1.98	
Sandy loam	0	11.60	10.83	13.63	13.63	±0.56
	250	10.65	8.97	7.64	3.86	

1) a. Strontium-89 and phosphorus mixed into the entire rooting zone (2 kg soil).
   b. Strontium-89 and phosphorus mixed into 150 g soil and placed as a 1 cm layer 4 cm below the soil surface.
   c. Strontium-89 sprayed on the soil surface followed by superphosphate broadcast and finally covered by 4 cm uncontaminated soil.
   d. Strontium-89 applied in a phosphorus solution which was evenly sprayed onto a soil surface and then covered by 4 cm uncontaminated soil.

Table 3 shows results from a microplot experiment with four soil types. The experimental technique was the same as that described in Ref. V. Radioisotopes, lime and superphosphate were placed in 25 cm depth and close contact between the contaminated soil and the lime (treatment E) and the superphosphate (treatment F) was assured. The effects of the treatments indicated in the table were measured in barley over a three-year period and in rye-grass over a four-year period. In one case addition of $CaCO_3$ initially increased the concentration of radiostrontium in the barley crops (Soil II) and the effects were generally small, whereas superphosphate reduced the uptake substantially. These results indicate that superphosphate may be a more effective method for reducing plant uptake of radiostrontium from typical Danish soils than the application of lime. The effect of phosphate is quite consistent and persisted through the seven-year experimental period.

Table 3

The effects of liming and superphosphate supply on the average concentration of strontium-90 in barley and rye-grass from experiments with four soils in microplots.
Data given as nCi strontium-90 per g of dry matter
(0.5 mCi strontium-90 per m^2 added 1964)

Soil Nos.[1]	Treatments	Barley, 1964-1966		Rye-grass			
		Grain	Straw	1967	1968	1969	1970
II	C, control	0.08	0.71	0.57	0.64	0.91	0.76
(s.c.l.)	E, lime	0.11	0.72	0.54	0.56	0.70	0.42
	F, superphos.	0.05	0.49	0.34	0.38	0.61	0.52
III	C, control	0.28	1.97	1.12	1.03	1.60	1.73
(s.c.l.)	E, lime	0.23	1.91	0.82	0.86	1.20	0.97
	F, superphos.	0.13	1.07	0.70	0.71	1.00	0.98
IV	C, control	0.18	1.90	1.72	2.29	2.71	2.83
(l.c.s.)	E, lime	0.18	1.69	1.26	1.94	2.14	1.85
	F, superphos.	0.09	0.92	0.90	1.50	1.42	1.53
V	C, control	0.23	1.99	1.75	1.78	3.01	2.24
(l.s.)	E, lime	0.17	1.31	0.92	1.04	1.73	1.50
	F, superphos.	0.10	0.83	0.89	1.00	1.59	1.47

1) s.c.l. = sandy clay loam; l.c.s. = loamy coarse sand; l.s. = loamy sand.

3.5. Variation between Plant Species and Varieties

When different plant species are grown in the same contaminated soil, widely different concentrations of strontium may be found in their tissues. A comparison between forty species (Ref. IV) showed a considerable variation in the concentration of radioactive strontium, but the total strontium uptake was closely related to that of calcium. The Sr/Ca ratio, calculated on the basis of total uptake, varied between 1.5 and 3.1 with a linear correlation coefficient of 0.98. However, among different plant parts wide variation in the Sr/Ca ratio occurred indicating discrimination between strontium and calcium during translocation. Similar results have been reported by Fuller and Flocker (1955), Frederiksson, Eriksson et al. (1958), Evans and Dekker (1962) and Haghiri (1964).

Several authors have presented data which demonstrate varietal differences in strontium accumulation within cereal crops (Rasmusson, Smith and Meyers 1963, Baker, Thomas and Gorsline 1964; Lee and Sosulski 1965). Substantial variation in strontium accumulation occurred between varieties, and evidence of a different Sr/Ca ratio was reported in barley seedlings by Young and Rasmusson (1966), in grain of barley and wheat by Smith, Rasmusson and Meyers (1963) and in mature wheat by Lee and Sosulski (1969). Contrary to these results Gorsline, Thomas, Baker and Ragland (1964) reported a consistent correlation between strontium and calcium in different genotypes of corn, and Bradford and Dale (1969) concluded from their studies that it is not likely that corn hybrids can be developed which accumulate high concentration of calcium and low concentration of strontium.

Table 4

Variation of strontium-90 and calcium content in sixty barley varieties grown in pot experiments 1965 and 1966

Content in dry plant material	Year	Grain			Straw		
		Max.	Min.	Mean	Max.	Min.	Mean
35 Two-rowed varieties							
nCi $^{90}Sr/g$	1965	0.40	0.21	0.32	4.32	2.27	3.21
mg Ca/g	1965	0.66	0.37	0.51	7.44	4.66	6.05
$^{90}Sr/Ca$, µCi/g	1965	0.61	0.57	0.63	0.58	0.49	0.53
nCi $^{90}Sr/g$	1966	0.48	0.26	0.35	5.43	2.34	3.75
mg Ca/g	1966	0.61	0.36	0.47	8.90	4.54	6.77
$^{90}Sr/Ca$, µCi/g	1966	0.79	0.72	0.74	0.61	0.52	0.55
25 Six-rowed varieties							
nCi $^{90}Sr/g$ *	1965	0.53	0.17	0.32	4.49	2.73	3.54
mg Ca/g	1965	1.04	0.32	0.58	7.96	5.19	6.70
$^{90}Sr/Ca$, µCi/g	1965	0.51	0.53	0.55	0.56	0.53	0.53
nCi $^{90}Sr/g$	1966	0.55	0.22	0.35	4.96	2.91	3.67
mg Ca/g	1966	0.78	0.41	0.57	8.71	5.04	6.73
$^{90}Sr/Ca$, µCi/g	1966	0.71	0.54	0.61	0.57	0.58	0.55

In order to elucidate the magnitude of variation in strontium and calcium accumulation by barley, sixty varieties were grown in contaminated soil in pot experiments in 1965 and 1966. The range of variation in strontium and calcium concentration is shown in table 4 together with the Sr/Ca ratios. The concentrations in straw were more than ten times as high as those in grain. The range of strontium-90 concentration in the grain of two-rowed varieties was from 0.21 to 0.40 nCi per g dry matter in 1965 and from 0.26 to 0.48 nCi in 1966; for the six-rowed varieties the concentration ranged from 0.17 to 0.53 nCi per g dry matter in 1965 and from 0.22 to 0.55 nCi in 1966, which indicates a greater variation between six-rowed than between two-rowed varieties. The Sr/Ca ratio tended to be slightly higher in the two-rowed than in the six-rowed varieties. An analysis of variance revealed that this was significant only for the ratio in grain and here the difference in the Sr/Ca ratio between varieties within the two groups also proved to be significant at the 0.1% level. The environmental conditions affected the accumulation of strontium and calcium differently since the Sr/Ca ratio was significantly different in the crops from the two years.

Emphasis has hitherto been given primarily to factors which may influence the amounts of strontium accumulating in crop plants, and the general similarities in the behaviour of strontium and calcium have been mentioned. The following sections will primarily be concerned with the Sr-Ca relationship in plants, and special attention will be paid to the effects of nitrogen nutrition, which have been shown to play an important role in the relative movement of strontium and calcium from soil to plant top.

4. THE STRONTIUM-CALCIUM RELATIONSHIP IN PLANTS

The extent to which strontium can substitute calcium in plant nutrition and the question of strontium toxicity to plants were the main purpose of the "pre-atomic age" experiments on the behaviour of strontium in the soil-plant system. Haselhoff (1893) reported that strontium appeared to substitute for calcium in plant nutrition and that no injurious effects on growth were found. Voelcker (1915) found that toxicity depended on the salt used, the chloride being toxic, while the sulphate, hydrate, and carbonate applied at similar rate were not injurious. McHarque (1919) reported that strontium carbonate could not be substituted for calcium carbonate in the growth of plants, but it was less toxic than barium in the absence of calcium carbonate. Slightly stimulating effects of partially substituting strontium for calcium were reported by Scharrer and Schropp (1937), who also found that the toxicity of strontium varied with plant species. Hurd-Karrer (1937) described the symptoms of strontium injury in wheat and found that the toxicity depended on the Sr/Ca ratio in the nutrient solution. The atomic ratio of strontium to calcium in plants was found by Collander (1941) to be almost equal to that in the nutrient solution, and Walsh (1945) found that strontium can largely replace calcium in the vegetative growth of plants but not in the formation of grain in cereals.

According to these early investigations it may be assumed that strontium can partially replace calcium and possibly stimulate the growth of plants when added together with calcium. More recent studies confirm these findings. It was shown that strontium may carry out some of the metabolic functions of calcium (Queen, Fleming and O'Kelley 1963). Maize seedlings remained alive in nutrient solutions when all the calcium was replaced by strontium, and it was indicated (Bonds and O'Kelley 1969) that strontium like calcium prevents toxicity by other nutrient ions, perhaps by maintaining membrane integrity and uptake selectivity. The two ions may, however, react differently in other metabolic processes as observed by Johnsson and Jackson (1966) for specific enzyme reactions. Calcium appears to be slightly more mobile in the plants than strontium (Schilling 1960) and, accordingly, more strontium than calcium occurred in acid soluble and insoluble forms in oat plants (Ringoet and de Zeeuw 1968 and Ref. XI).

Much experimental work concerned with radioactive strontium has been based upon the assumption that strontium behaves like calcium in the soil-plant system. However, from this work considerable evidence has accumulated which indicates important differences in behaviour of the two elements. It has been shown that the relative uptake and distribution of strontium and calcium in plants may be greatly influenced by the environmental growth conditions. In the following chapter an attempt will be made to evaluate some of the processes in which the relative movement of the two elements may be changed when the growth conditions are varied by the addition of nitrogen.

5. THE STRONTIUM-CALCIUM RELATIONSHIP IN OATS AS INFLUENCED BY NITROGEN

It has been mentioned above that nitrogen nutrition affected the relative distribution of strontium and calcium differently in oats grain and straw.

The Sr/Ca ratio in grain decreased relative to that in straw so that the distribution factor (DF) decreased with increasing nitrogen supply (Figure 2).

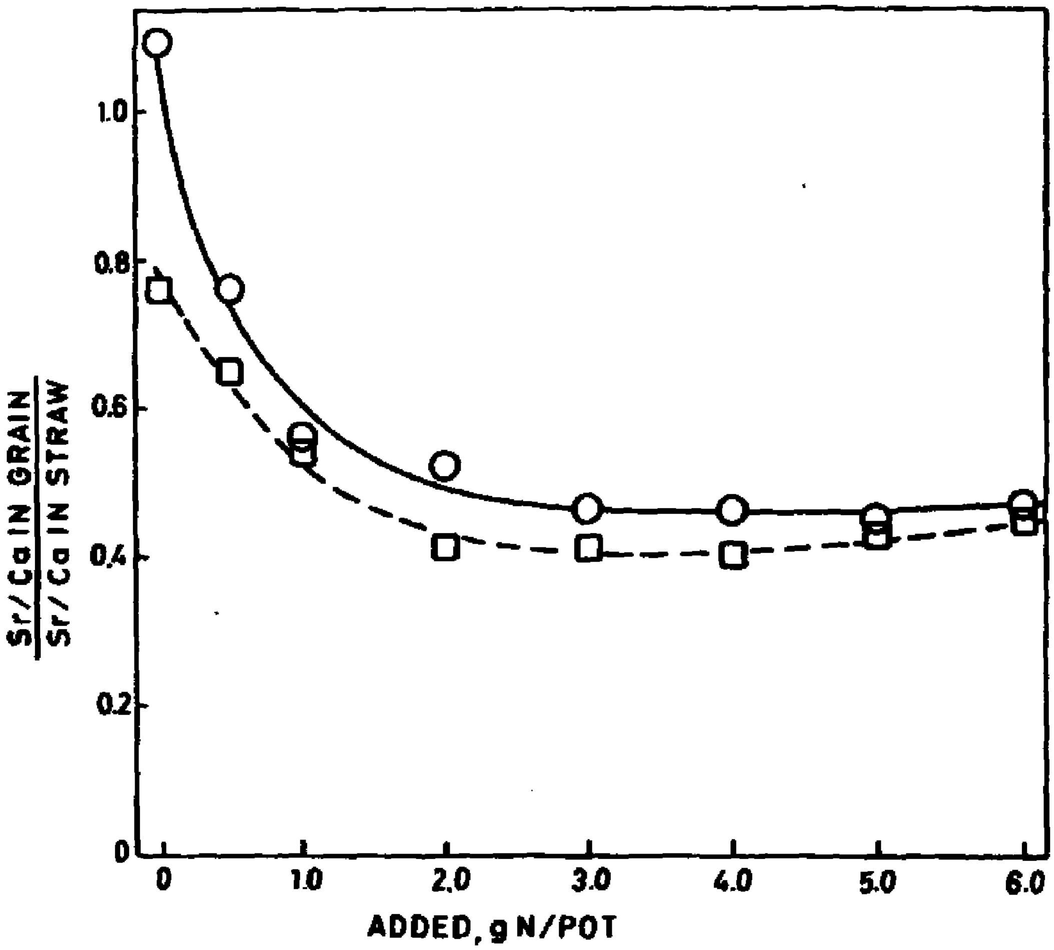
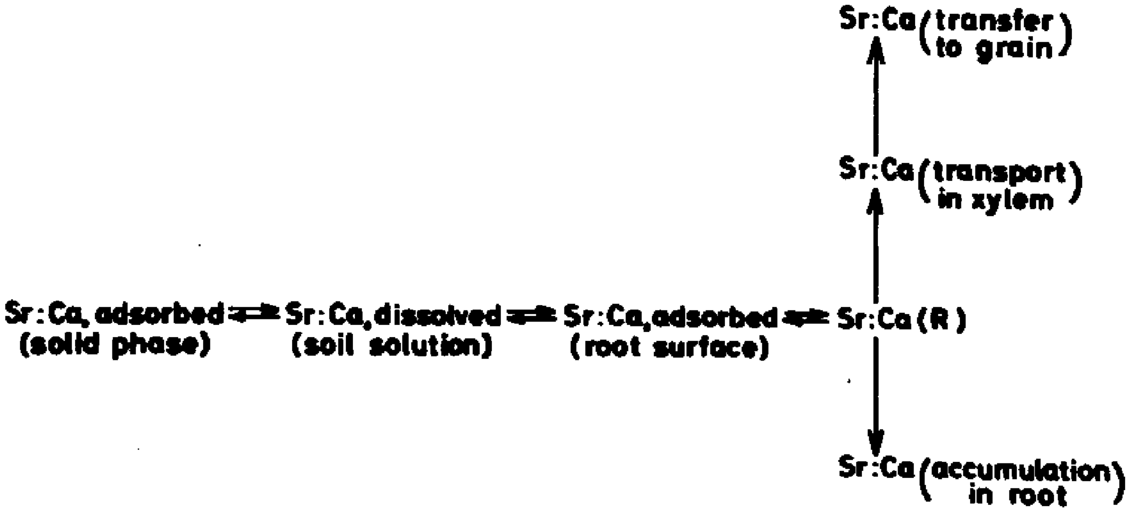


Figure 2. The Sr/Ca ratio in oat grain relative to that in oat straw as influenced by nitrogen supply. The upper curve (solid line) represents the relationship calculated on the basis of strontium-90 and calcium-45 while the lower curve (broken line) is calculated on the basis of strontium-90 and stable calcium.

Addition of nitrogen may influence the ratio in which strontium and calcium accumulate in different plant parts both before and after the ions are absorbed by the roots. An attempt to evaluate the effects of nitrogen should consequently involve considerations of the sequence of reactions which affects the strontium-calcium movement from the soil-solid phase to the plant top. The over-all picture of the strontium-calcium uptake may be summarized by the following equation:



where (R) denotes the ion carrier which mediates the transfer of ions through cell membranes. The movement from the solid phase through the soil solution into the roots is assumed to be reversible processes while the transport inside the plants is uni-directionally mainly from root to top.

When the plants are grown in soil containing both strontium and calcium, the ratio in which the two ions accumulate in seeds may be influenced by: 1) the strontium-calcium ratio in the soil solution; 2) the transport of strontium and calcium in the soil solution to the root adsorbing surface; 3) the uptake and transport in the root tissue; 4) the upward transport in the conducting tissue, and 5) the transfer from the conducting system to grain. The effects of nitrogen nutrition on the Sr/Ca ratio in each of these separate steps will be evaluated in the following. The discussion is based on data from pot experiments with oats (Refs. I, VI, VIII, X and XI) and water-culture experiments with wheats (Ref. IX) and oats (Refs. VII and X). Since nitrogen is supposed to be present in most soils as nitrate, this form of nitrogen was also used in most of the water-culture experiments.

5.1. The Strontium-Calcium Ratio in the Soil Solution

The distribution of strontium between the solid phase and the soil solution differs from that of calcium. In the equilibrium reaction:

$$\text{Soil-Ca} + Sr^{++} \rightleftharpoons \text{Soil-Sr} + Ca^{++}$$

strontium is, to a greater extent than calcium, adsorbed on the exchange complex of mineral soils. Differences between soils occur because of variation in the nature of the exchange complex, and for organic soils the selectivity coefficient (K_c) may be less than unity, indicating a preferential adsorption of calcium as discussed in section 3.1. It may affect the relative distribution of strontium and calcium in different plant parts if this equilibrium reaction proceeds during the growing period.

Strontium found in oat grain was shown to be absorbed relatively late in the growing period (Ref. VII), and the same may be true for calcium. Both ions are transported uni-directionally from root to top and are not redistributed to any measurable extent within the plants. Consequently a continuous supply of calcium has to be available throughout the growing season in order to avoid calcium deficiency. That the Sr/Ca ratio found in grain is lower than in straw might, at least to some extent, have been caused by a change with time of the Sr/Ca ratio in the soil solution. That such an effect could be found was clearly indicated by comparing the specific activity of calcium in oat grain and straw (Ref. VIII). The specific activity was lower in grain than in straw. Similarly, both the $^{85}Sr/Ca$ and the $^{45}Ca/Ca$ ratios in rye-grass (Ref. X) decreased with the time, indicating that equilibrium between the added radioisotopes and native calcium had not been obtained. The equilibration reactions apparently proceeded during the growing period.

An alternative explanation might be that some soil calcium, which did not undergo exchange with the added radioisotopes, was absorbed by the plants. The successive depletion of the soil for calcium may render otherwise unavailable calcium available for absorption. The very small portion of the soil calcium which is absorbed by the plants may indicate, however, that this explanation is not very likely. Nevertheless the plant roots are not in close contact with more than a few per cent of the soil particles and this portion may be exhausted for calcium as a result of the uptake in the plants. Such exhaustion of the rhizosphere may render some "extra" calcium available to plants (Newbould 1963; Newbould and Russell 1963). The data discussed by Barber (1968) and Halstead, Barber, Warnche and Bole (1968) actually support the suggestion that the rhizosphere may be exhausted for calcium by some plant species.

5.2. Transport to the Roots Adsorbing Surface

The rate of ion uptake into the root of a plant is closely related to the concentration or intensity of the ion in the solution immediately adjacent to the root surface. As only a small portion of the soil solution is in contact with the plant root, uptake may be limited and discrimination may occur during the transport of ions to the root surface. The movement of ions in the soil solution is supposed to occur by mass-flow and diffusion. In addition to these transport processes, Barber, Halstead and Follet (1966) proposed that root interception, i. e. the effect of the root on its environment as it grows through the soil, is also a significant factor in ion supply to roots. Definitions of each of these mechanisms, and procedures for calculating them, have been given by Oliver and Barber (1966) and their relative importance has been evaluated by Barber (1968), Halstead, Barber, Warncke and Bole(1968) and Riley and Barber (1970). If the supply of ions by root interception and mass-flow is less than the amount taken up by the root, then the concentration immediately adjacent to the root surface, the rhizosphere, will be lowered and diffusion of ions towards the root may occur. If root interception and mass-flow supply more ions to the root than are absorbed, then the concentration in the rhizosphere increases and diffusion away from the root may occur.

According to Barber's and co-worker's results, mass-flow and root interception account for all the transport of strontium and calcium to the roots of most plant species grown in normal agricultural soils. Diffusion of the two ions to roots was important only when high calcium-requiring plants, such as tomatoes, were grown under conditions where the rate of transpiration was limited by high air humidity (Barber 1971). Under such conditions, the Sr/Ca ratio absorbed by tomato roots was similar to the ratio adsorbed on the soil exchange complex. This transport mechanism was designated by Barber as "exchange diffusion" rather than solution diffusion. Since oat is considered a low calcium-requiring plant species it may be reasonable to assume that transport by such "exchange diffusion" does not cause any discrimination between strontium and calcium.

Although a change with time in the relative availability of strontium and calcium may cause the Sr/Ca ratio in grain to be lower than in straw, the effects observed after nitrogen supply cannot be explained by such processes. The distance between the two curves shown in fig. 2 may represent the effects of a change in relative availability. The added radioactive strontium continues to equilibrate with the native (stable) calcium in the soil during the growing period, whereas equilibrium is rapidly attained with the simultaneously added radioactive calcium. Both curves do, however, decline with increasing nitrogen supply. This indicates that the effects of nitrogen could not be ascribed to processes in the soil. The physiological processes which regulate the relative uptake and transport of strontium and calcium in the plant may be changed by addition of nitrogen.

5. 3. Uptake and Transport in Roots

Ion uptake and transport across the root tissue to the stele have been the subject of intensive studies for many years and several theories about the processes involved have been advanced (cf. Lundegårdh 1955; Epstein 1956; Robertson 1958; Fried and Shapiro 1961; Sutcliffe 1962; Brouwer 1965). No attempt will be made here to discuss the nature of the processes regulating the uptake and transport of strontium and calcium in roots. The uptake is assumed to occur in two steps: 1) An initial rapid adsorption which is considered a result of cation exchange and ion diffusion in cell walls and intercellular spaces, the apparent free space (AFS), as described by Briggs and Robertson (1957), and 2) an absorption phase in which the strontium and calcium are moved across the protoplasmic membrane into the cytoplasm. The transport across the epidermis, cortex and endodermis to the xylem duct may occur in the symplast (inside the cells) or in cell walls and intercellular spaces. The extent to which the transfer of strontium and calcium from the external solution to the xylem duct requires metabolic energy is not fully known. In the schematic equation (p. 27) for this transport of strontium and calcium it is indicated that the absorption phase is mediated by a carrier mechanism, which may require metabolic activity. In addition to this active uptake it is likely that ions under certain conditions may be transported passively in the transpiration stream. However, considerable differences of opinion exist as to the importance of passive transport (Brouwer 1965).

Separation of adsorbed and absorbed fractions. In the experiment with wheat (Ref. IX) and oat seedlings (Ref. X) the two fractions of strontium and calcium were separated by desorbing the exchangeable radioisotopes from the root tissue at the end of each uptake period. The time course of desorption of strontium-85 and calcium-45 from oat roots to an inactive solution of the same composition as the uptake solution is shown in Figure 3. The initial rapid desorption is followed by a slow exchange, which continues for several hours. The first part of the desorption curve may represent the release of radioactive strontium and calcium from readily accessible exchange sites on the surfaces of cell walls, whereas the slowly exchanging component may be bound within cell walls (Drew and Bidduiph 1971). This latter portion may be related to metabolically accumulated strontium and calcium (Barber and Shone 1967). It should be noted that relative more calcium-45 than strontium-85 is desorbed. This is in accordance with the previously mentioned fact that calcium is more mobile than strontium.

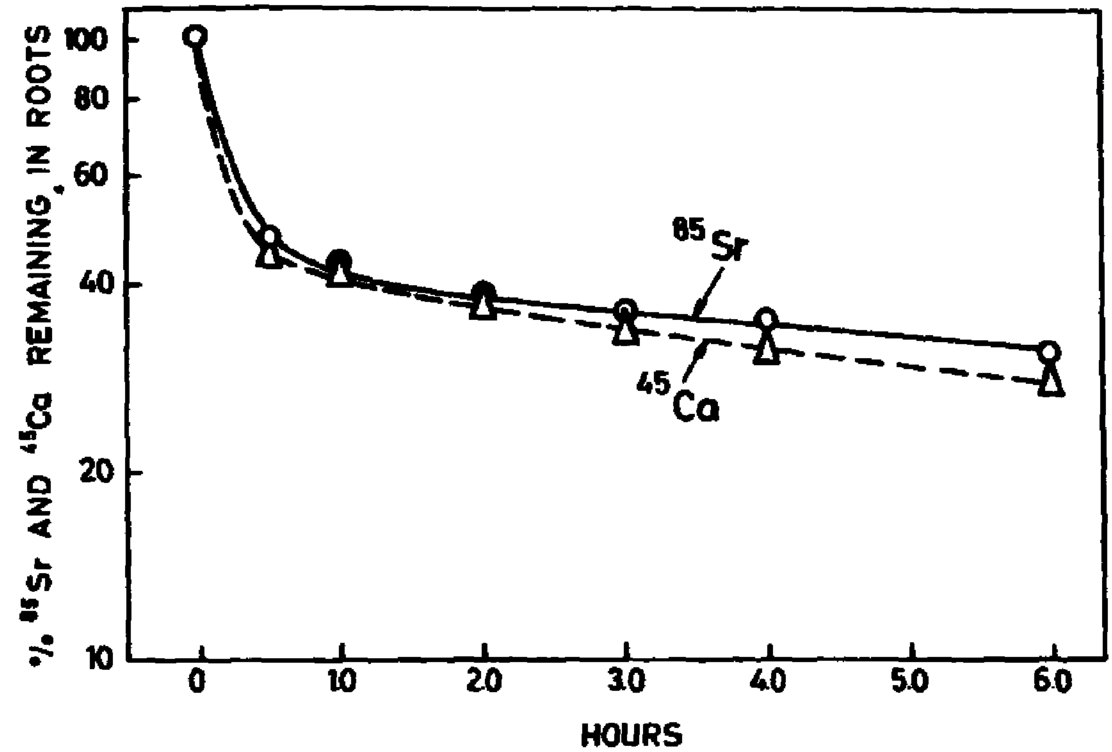


Figure 3. Desorption of strontium-85 and calcium-45 from excised oat roots versus time. The intact plants had previously taken up the two isotopes from a double labelled solution containing 2 meq Sr + Ca per litre (Sr/Ca = 1/400). The exchange solution was an inactive solution of the same composition as the uptake solution.

A clear distinction between adsorbed and absorbed ions is not possible. The absorbed fraction of the strontium-85 and calcium-45 remaining in roots after desorption of the readily displaced fraction may contain a small portion of adsorbed ions in addition to a fraction metabolically absorbed in root tissue and a small portion which is "en route" to the shoot.

Influence of Strontium-Calcium Concentration

The relationship between the adsorption and absorption phases is not known. Both wheat (Ref. IX) and oat (Ref. X) roots seem to have a greater affinity for strontium than for calcium since strontium was adsorbed in preference to calcium. This preferential adsorption of strontium for calcium was only little influenced by nitrogen addition, but greatly dependent on the Sr/Ca ratio and the Sr-Ca concentration in the external solution (table 5 and Ref. IX table 1). The non-exchangeable (absorbed) fraction found in roots also depended on the concentrations of the two ions in the nutrient solution and the $^{85}Sr/^{45}Ca$ ratio in this fraction varied from that found in the adsorbed pool.

Table 5

The $^{85}Sr/^{45}Ca$ ratios in roots, shoots and in a fraction desorbed from roots to unlabelled solution. The oat seedlings were grown for 20 h in solutions containing different concentrations of Sr + Ca (Sr/Ca = 1/400) and 5 μCi each of ^{85}Sr and ^{45}Ca per litre

Uptake solution meq/litre	Desorbed	Roots	Shoots	Total accumulated
0.4 $Sr\text{-}Ca/Cl_2$	1.4	2.7	0.56	2.0
0.4 $Sr\text{-}Ca(NO_3)_2$	1.4	2.3	0.77	1.5
2.0 $Sr\text{-}CaCl_2$	1.6	1.7	0.53	1.3
2.0 $Sr\text{-}Ca(NO_3)_2$	1.6	1.4	0.66	1.0
10.0 $Sr\text{-}CaCl_2$	1.9	1.0	0.61	0.9
10.0 $Sr\text{-}Ca(NO_3)_2$	1.7	1.0	0.73	0.9

The results indicate that the plant roots absorb the two ions in a ratio different from that adsorbed on the external surface of root cells. Consequently it may be concluded that the absorption phase involves a mechanism which discriminates between strontium and calcium and this mechanism seems to be influenced by the presence of nitrate in the nutrient solution.

The difference in relative uptake of strontium-85 and calcium-45 caused by variation in the external concentrations may be explained by the hypothesis advanced by Epstein and Hagen (1952). They assume that the absorption of inorganic ions involves the existence of several distinct carrier sites, which vary in their affinity for various cations. The capacity of such specific carriers may vary so that uptake studies from low concentration may differ appreciably from results obtained from experiments using higher concentrations of the ions in question (Epstein 1966). If it is assumed, as illustrated in fig. 4,that a carrier (A) with a low capacity has a higher affinity for strontium than for calcium while a second carrier (B) does not discriminate between the two ions, then a preferential accumulation of strontium will occur at low external concentrations as was the case with wheat and oat seedlings (Refs. IX and X). At higher concentrations carrier B may dominate and the Sr/Ca ratio absorbed by the plants will consequently approach the ratio which is present in the external nutrient solution. Evidence for at least two such carrier sites for strontium was reported by Fried and Noggle (1958) and they suggest that strontium and calcium sites may be identical at a relatively high ion concentration, which agrees with the results we obtained. An alternative explanation of the difference in re-

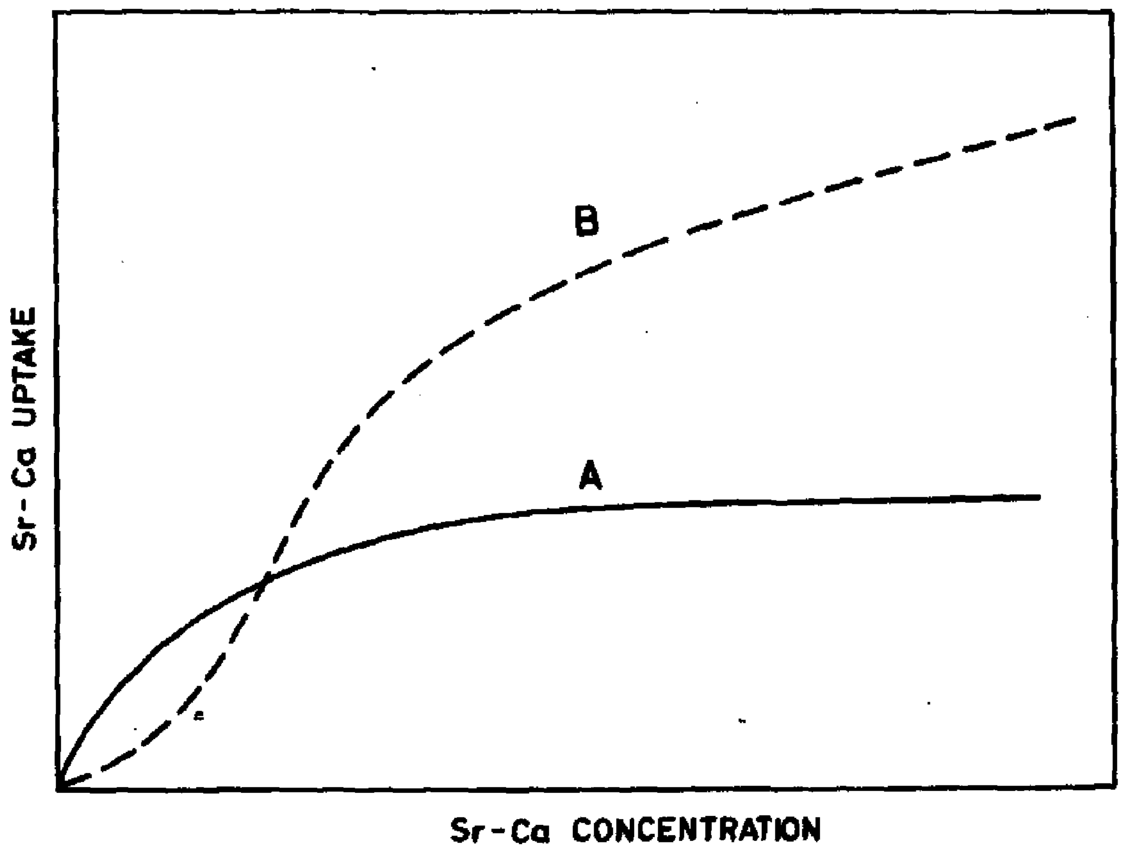


Figure 4. A schematic illustration of the strontium and calcium uptake in plant roots when mediated by two carrier mechanisms having different affinity for the two ions. Carrier A is assumed to transport strontium in preference to calcium, while carrier B does not discriminate between them.

lative uptake of strontium and calcium at low and high concentrations may be that only part of the uptake is mediated by a carrier depending on metabolism, while another part is transported indiscriminatorily in the transpiration stream to the xylem duct. In this case carrier B in figure 4 may represent this passive mechanism.

Influence of Nitrate

The interrelationship between calcium and nitrogen was investigated by Burstrøm (1954) who found that calcium was required for nitrate uptake by wheat roots. Similar results were obtained by Minotti, Williams and Jackson (1968 and 1969). They found that the rate and capacity of N-depleted wheat seedlings to absorb nitrate were increased when calcium was supplied in the nutrient solution. Conversely, the addition of nitrate stimulated the uptake of calcium and other cations including strontium (Jackson, Williams and Minotti 1968; Jackson and Williams 1968). This accords well with our results with N-depleted wheat (Ref. IX) and oat seedlings (Ref. X). The presence of nitrate in the double labelled nutrient solution stimulated the uptake of radioactive strontium and calcium.

The mechanism by which calcium facilitates the absorption of nitrate is not quite understood. It is generally accepted that calcium affects the permeability and selectivity of cell membranes but an additional mechanism is assumed to operate. Burstrøm (1954) suggested that calcium may be necessary for the formation of some specific carrier for nitrate during the initial phase of absorption. It has also been proposed, as discussed by Minotti, Williams and Jackson (1968), that calcium facilitates the diffusion of anions to the sites of active absorption by neutralizing negatively charged sites at the root surface or in the cell wall. Such an effect may be obtained by use of other polyvalent cations (Franklin 1969), and the stimulation has been found to be greater for a divalent anion than for a monovalent anion (Franklin 1971).

The stimulation in strontium and calcium uptake by the presence of nitrate in the nutrient solution may partly be explained by nitrate acting as a counterion to maintain electro-neutrality and thereby increasing ion-mobility. Another factor which may influence the cation uptake is the lowering of solution acidity associated with rapid nitrate uptake. Influence of this latter factor was avoided by buffering the uptake solution to pH 6.5. The increased strontium-85 and calcium-45 uptake obtained (Refs. IX and X) cannot be explained solely as a consequence of a simultaneous, rapid nitrate uptake. Nitrate absorbed several days before the oat seedlings were transferred to the uptake solution induced an enhanced ability for strontium and calcium uptake. Consequently at least part of the observed effects is caused by metabolic events taking place after the nitrate accumulated in root cells. Probably the important factor is an increased translocation of strontium and calcium associated with the nitrate assimilation. The fact that ammonium and urea stimulated the translocation of strontium-85 and calcium-45 (Ref. IX) supports the assumption that assimilation products of nitrate may also increase the translocation.

The uptake of strontium and calcium was not stimulated to the same extent by nitrate addition. At Sr/Ca ratios and concentrations similar to those existing in normal soils the calcium absorption is stimulated more than that of strontium so that the Sr/Ca ratio in root tissue is lowered (table 5, Refs. IX and X). At a low Sr-Ca concentration (0.4 meq/l) in the nutrient solution strontium-85 is absorbed in roots in preference to calcium-45 and the $^{85}Sr/^{45}Ca$ ratio absorbed is even higher than that found in the adsorbed fraction. The presence of nitrate diminished the preferential absorption of strontium-85 over calcium-45 so that the $^{85}Sr/^{45}Ca$ ratio in the root tissue decreased. This may indicate that nitrate influences the ability of plant roots to discriminate between strontium and calcium in the absorption phase, which requires metabolic activity. However, the $^{85}Sr/^{45}Ca$ ratio in shoots increased (table 5) indicating a greater stimulation of the transport of strontium than of calcium to shoots. Results from other experiments (Ref. IX) showed a $^{85}Sr/^{45}Ca$ ratio greater than one in the shoots and a decrease by addition of nitrate. Since the ratio in the external solution was always 1:1 these results may indicate that the increased uptake due to nitrate to some extent occurred without discrimination between the two ions - through carrier B (figure 4) or passively in the transpiration stream. However, a comparison of the ratio based on total accumulation indicates that high concentration and nitrate addition favour the uptake of calcium at the expense of strontium so that the ratio in the plant is lowered relative to that in the external solution.

5.4. Upward Transport in the Plants

A continued strontium and calcium absorption by the roots is dependent upon transfer of the absorbed ions to the above-ground plant parts. It is generally accepted that this upward transport occurs in the xylem and that the ions are exposed to a series of exchange reactions on negatively charged sites at the cell walls. Strontium is, to a greater extent than calcium, retained on these sites so that the Sr/Ca ratio arriving at the upper part of the plant is lower than that delivered by the root to the xylem duct. The effects of nitrogen nutrition on the relative transport of strontium and calcium in oat and wheat seedlings and in excised oat culms are reported in Refs. IX and X.

Transport in Seedlings

Increases in strontium and calcium transport to shoots as a consequence of nitrogen nutrition have been observed in N-depleted seedlings of oat and wheat. This nitrogen-stimulated transport was obtained under conditions where nitrate and the two cations were supplied in the uptake solution as well as with nitrate pretreatment of the seedlings. Furthermore, an increased transport to shoots was obtained by the addition of ammonium and urea to the uptake solution even though the accumulation of strontium and calcium in roots tended to decrease when ammonium was used (Ref. IX). It should, however, be emphasized that nitrate proved to be much more effective than the two reduced forms of nitrogen.

The stimulation in transport resulting from the presence of nitrate occurred primarily during the period in which the nitrate uptake had been shown to be most rapid (Ref. X). This might indicate that presence of nitrate ions is a prerequisite for the rapid transport of strontium and calcium in the xylem. Presumably this requirement is only for the deposition into the xylem duct (Jackson and Williams 1968) since the upward movement occurs as a sequence of cation exchange reactions. The effect of nitrate on the rate of transport may then partly be indirect, e. g. by increasing the rate of transpiration. A clear distinction between uptake and transport processes is impossible in experiments with intact seedlings. The observed effects of the reduced forms of nitrogen and of nitrate pretreatment suggest, however, that nitrogen metabolism stimulates the transport of strontium and calcium apart from its influence on uptake processes.

Associated with the increased transport a change is noted in the $^{85}Sr/^{45}Ca$ ratio in shoots, which indicates the presence of a nitrogen-dependent discriminatory mechanism. This may be situated in the root, and may be explained by the influence on the uptake as discussed in section 5.3. The capacity of the root tissue for preferential accumulation of strontium over calcium may have been saturated by the increased uptake due to the presence of nitrate. The discrimination between the two ions may thereby have been diminished in a similar way as when the external concentration is increased (table 5).

Transport through Excised Culms

Discrimination between strontium and calcium caused by absorption and transport in root tissue was avoided by severing the roots from the plants shortly after flowering, and allowing direct access of the labelled solution into the stems. Investigations were made on the rate of transport through stems of oat plants, which have been grown in pot cultures at different nitrogen levels until flowering (Ref. X). The amounts of calcium transported to the maturing panicles always exceeded that of strontium and a greater quantity of both ions was transported in high-N than in low-N plants. The results confirm those of others (Russell 1963), namely that strontium is retained in preference to calcium in the stem. This may be explained by the suggestion (Bell and Biddulph 1963; Emmert 1965) that the stem acts as a cation exchange column in which strontium is retained in preference to calcium. The increased transport due to nitrogen may be explained by an increased rate of transpiration.

Nitrogen apparently also affected the cation exchange properties of the stem since the $^{85}Sr/^{45}Ca$ ratios found in panicles from high-N plants was lower than those in low-N panicles. These results agree with the data obtained with intact plants grown to maturity in pot experiments (Ref. XI) and may contribute to the change in the distribution pattern generally found in oats supplied with increasing amounts of nitrogen.

Transfer of Strontium and Calcium to Grain

The process of ion translocation to plant seeds is a relatively neglected problem. Much more attention has been paid to the physiology of ion uptake by roots than to the transfer of mineral elements from the vegetative plant parts to the next generation - the seeds. Much work has been devoted to the translocation of organic compounds but very little to ion accumulation in grain. To my knowledge no results of investigations on the physiology of strontium and calcium transfer to oat grain have been published. However, Craker and Smith (1969) have investigated the mechanism of strontium accumulation in wheat grain. They cited anatomical studies of the vascular system and assumed that the ion sources available for developing grain are the xylem stream of the rachis. Their studies indicated that the transfer of strontium to grain is accomplished by active metabolic processes probably similar to those based on the carrier principle in root absorption studies.

By analogy with Craker's and Smith's suggestions for wheat it may be assumed that the immediate strontium and calcium sources for the oat grain are the flower stalks. The $^{85}Sr/^{45}Ca$ ratios in flower stalks were considerably higher than in grain and glumes (Ref. X). The discrimination factors, calculated as the $^{85}Sr/^{45}Ca$ ratios in grain and glumes relative to the ratios in flower stalks, are shown in table 6.

Table 6

Discrimination factors for the transfer of strontium-85 and calcium-45 from flower stalks to grain and glumes of excised oat plants placed in double labelled Sr-$CaCl_2$ or Sr-$Ca(NO_3)_2$

Pretreatments gN/pot	Uptake treatments	$\frac{^{85}Sr/^{45}Ca \text{ in grain}}{^{85}Sr/^{45}Ca \text{ in flower st.}}$	$\frac{^{85}Sr/^{45}Ca \text{ in glumes}}{^{85}Sr/^{45}Ca \text{ in flower st.}}$
0	Sr-$CaCl_2$	0.36	0.51
	Sr-$Ca(NO_3)_2$	0.28	0.45
0.5	Sr-$CaCl_2$	0.35	0.54
	Sr-$Ca(NO_3)_2$	0.21	0.45
1.5	Sr-$CaCl_2$	0.31	0.38
	Sr-$Ca(NO_3)_2$	0.22	0.36
3.0	Sr-$CaCl_2$	0.26	0.55
	Sr-$Ca(NO_3)_2$	0.24	0.36

It is evident that the transfer to grain of strontium relative to that of calcium decreased with increasing N-supply in the pretreatment, whereas such an effect could not be seen in glumes. The presence of nitrate in the uptake solution, however, increased the discrimination against strontium relative to calcium at the transfer of the two ions both to grain and to glumes. The presence of nitrate apparently stimulates the movement of calcium more than that of strontium. This may be independent of metabolic activity but associated with the rapid movement of the nitrate ion in the conducting system. The increased discrimination obtained by pretreatment with nitrogen is presumably caused directly by active processes or the effects may be indirect by some assimilation products of nitrate influencing the ion transfer. The differences between discrimination factors describing the relative transfer to grain and glumes may be caused by strontium and calcium being accumulated in glumes by passive processes, while the accumulation in grain is to some extent regulated by metabolic processes. This would be in agreement with the conclusion drawn by Craker and Smith (1969) for wheat. The present study with oats indicates that nitrogen nutrition may enhance the discrimination against strontium relative to calcium, both when the two ions are passively transported and when the translocation depends on metabolic activity in the plant.

6. GENERAL DISCUSSION AND CONCLUSIONS

In assessing the consequences of contamination of agricultural areas with radioactive strontium, it is important to know the influence of such factors as plant species, soil types, cultivation practices, liming and mineral fertilization on the amounts transported from soil to plants. Investigations on the effects of these factors under Danish conditions are summarized in the preceding chapters. The following is a general discussion of the main effects obtained and the conclusions which can be drawn from the investigations.

The uptake of added radioactive strontium varies greatly between plant species. Among the species normally used as agricultural crops, the gramineae generally have a low concentration of strontium while the legumes accumulate much higher concentrations of strontium. However, considerable variations occur within a given botanical family, and even the variations between varieties of the same species may be important, as indicated in section 3.5.

The uptake of strontium is closely related to the uptake of calcium and the main factor governing the strontium uptake from contaminated soils is the content of exchangeable calcium. However, some deviation from this general trend occurs and other factors may considerably influence the relative uptake of the two ions as will be discussed below. The maximum difference found in strontium uptake from typical Danish soils was about one order of magnitude. The uptake from a heavy clay loam may be only one tenth of that from a light sandy soil with a low pH.

Cultivation practices can affect the uptake of radioactive strontium in various ways. Deep ploughing as compared to superficial cultivation of newly contaminated areas may reduce the uptake of radioactive strontium by a factor of 2 to 5 depending on soil type and plant species. The most effective reduction is generally obtained on heavy clay loam. The combined effects of deep cultivation and selection of shallow-rooted crops may be of practical interest in case of a serious contamination of agricultural areas. Special remedial measures, such as removing the contaminated soil layer and high temperature treatment (Ref. III), have been considered and experimentally tested. Such drastic methods are, however, not likely on a large scale and therefore of limited practical interest.

Application of lime, which is commonly considered one of the most effective means for the reduction of plant uptake of radioactive strontium, is rather ineffective if the degree of calcium saturation is high as is the case in most of our agricultural soils in Denmark. A much more effective reduction of the strontium uptake was obtained through ample application of water-soluble phosphates, provided that close contact between the contaminated soil layer and the phosphate was assured. The reduction is presumably caused partly by competition from calcium occurring in phosphates and partly by a precipitation of slightly soluble strontium phosphates, which may reduce the concentration of radiostrontium in the soil solution and thereby render it less available for plant uptake.

Contradicting results have been reported on the effects of fertilizers containing potassium and magnesium. In general, cations added with fertilizers may compete with radioactive strontium for the adsorption sites on the soil-solid phase and thereby increase the availability to plant uptake. On the other hand an increased concentration of potassium and magnesium in the soil solutions may reduce the uptake because of competition with the radioactive strontium during the initial phase of uptake into the plant roots. The relative importance of these counteracting effects is difficult to predict. Generally we obtained a small decrease in strontium uptake by the addition of fertilizers containing potassium and magnesium; however, the effects are of minor practical importance.

Investigations on the comparative behaviour of strontium and calcium in soils and plants have revealed great similarity but have also shown that discrimination between the two ions may occur. A preferential adsorption of strontium is normally found in mineral soils so that the strontium concentration in the soil solution (the availability) is relative less than that of calcium. On the other hand, evidence from water culture experiments indicates that strontium is also preferentially adsorbed on root surfaces when the concentration of strontium and calcium is as low as in normal soil solutions. These two factors may counteract each other so that the relative accumulation of the two ions in plants may be quite similar to the ratio in which they occur in soils. In the concentration range found in soil solutions it may furthermore be expected that strontium absorbed in root tissue is retained in preference to calcium so that the Sr/Ca ratio found in shoots is lower than that in roots. It was shown that relatively more strontium than calcium occurs in compounds of stronger chemical bindings (Ref. XI). This may explain some of the discrimination against strontium occurring during transport of the two ions within the plants.

The relative distribution of strontium and calcium in different plant organs may be affected by changes in equilibrium reactions in the soil/soil solution system (isotopic exchange). When water-soluble radioactive strontium is mixed into the experimental soil it starts to equilibrate with soil calcium (and strontium). This process may proceed during the growing period so that the Sr/Ca ratio to which the plant roots are exposed changes with time. Since these two cations are transported directly to the plant organ under development and are not redistributed (Ref. VII) within the plant, the ratio in a particular organ is a picture of the relative availability during the time of development. It was shown (Ref. VIII) that the Sr/Ca ratio in oat grain could be lesser than in oat straw because of a change in relative availability from the start of the growing period to the time for grain development.

Nitrogenous fertilizers are extensively used in modern agriculture to enhance the quantity and quality of crops. This may influence the accumulation of other mineral elements including strontium and calcium. It was indicated in the very first report (Ref. I) in this series of investigations that nitrogen affected the uptake and distribution of strontium and calcium differently. It was, therefore, decided to elucidate in more detail the influence of nitrogen nutrition on uptake and transport of strontium and calcium in oat plants. The evidence obtained from double labelled water culture and pot experiments led to the conclusion that nitrate stimulates both the active and the passive transport of strontium and calcium in plants. Associated with the stimulation is a change in discrimination between the two elements so that the Sr/Ca ratio in grain decreases in relation to the ratio in the vegetative parts of the plants. In support of this general postulate the following findings should be emphasized:

1) The increased uptake and transport occurred during the period of

the most rapid nitrate uptake (Ref. IX), which indicates that the two cations may accompany the nitrate anion and be transported "passively" as counterions for the negatively charged anions.

2) Nitrate stimulated the uptake of strontium and calcium when it was present in the uptake solutions but also if it was supplied to the seedlings several days before they were exposed to the double labelled Sr-$CaCl_2$ solution (Refs. IX and X). Moreover, reduced forms of nitrogen (ammonium and urea) also increased the transport of strontium and calcium in wheat seedlings. Presumably some assimilation products of nitrate are responsible for the effects obtained when the seedlings were pretreated with nitrate, and protein synthesis may be a prerequisite for the active absorption of ions.

3) The strontium and calcium absorptions, which are considered the metabolically active phase of the uptake processes, were both stimulated by nitrogen nutrition but more so for calcium, which resulted in a lowered Sr/Ca ratio in the non-replaceable pool in the root tissue. The fact that the Sr/Ca ratio in shoots of oat (Ref. X) and wheat (Ref. IX) seedlings were approaching the ratio present in the external solution may, however, indicate that the increased transport due to nitrogen occurred with less discrimination between strontium and calcium than it did in N-depleted seedlings.

4) The upward movement of strontium and calcium in excised culms was increased by nitrogen, and the Sr/Ca ratio reaching the plant top was lower in high-N than in low-N plants. The relative transfer of strontium and calcium to glumes was independent of the pretreatment but influenced by the presence of nitrate in the uptake solution (transport as counter ions). The relative transfer of the two ions to the grain was, however, affected both by nitrogen pretreatment and the presence of nitrate in the uptake solution (table 6). Metabolically active processes may consequently to a great extent regulate the ratio in which strontium and calcium are absorbed by plant roots and also the ratio in which they are delivered to the next generation - the grain.

The results obtained under well-defined growing conditions in water culture thus confirm the findings in pot experiments, namely that the ability to discriminate between strontium and calcium depends upon the nutritional status of the oat plants. The data indicate two contrasting effects of nitrogen which may be of value in evaluating the consequences of radioactive strontium contamination of agricultural areas. One effect is the increased uptake due to nitrogen supply. The other effect is counteracting the former since the calcium uptake is enhanced even more than the strontium uptake. The relative translocation of strontium to grain is decreased resulting in a considerable decreased Sr/Ca ratio in the grain. It should, however, be emphasized that so far these effects have only been ascertained in oat plants.

ACKNOWLEDGEMENTS

The work summarized in this report was performed in the years 1960-1971. The major part of the experiments was carried out at the Atomic Energy Commission Research Establishment Risø, and the author is grateful for the excellent working conditions provided. I am very grateful to the whole staff of the Agricultural Research Department at Risø for their friendly co-operation, valuable discussions, many suggestions and expert technical assistance.

I am deeply indebted to Professor W. A. Jackson for encouragements and inspiring discussions during my recent stay at the Soil Science Department, North Caroline State University, U.S.A. I am also much indebted to Professor, dr. agro. F. Steenbjerg for valuable suggestions and advice during the preparation of this report.

DANSK RESUMÉ

PLANTERNES OPTAGELSE AF RADIOAKTIVT STRONTIUM MED SÆRLIGT HENBLIK PÅ KVÆLSTOFERNÆRINGENS INDFLYDELSE PÅ STRONTIUM-CALCIUM FORHOLDET

Afhandlingen resumerer og diskuterer en række tidligere offentliggjorte undersøgelser over planternes optagelse af radioaktivt strontium. De tidligere offentliggjorte arbejder er anført på side 7-8 og er i teksten betegnet med romertal I-XI.

Undersøgelserne blev påbegyndt i begyndelsen af 1960-erne foranlediget af den stigende forurening af omgivelserne med radioaktivt nedfald, som var en følge af stormagternes prøvesprængninger af kernevåben. De helsefysiske problemer, der kan opstå i forbindelse med radioaktivt nedfald, består dels i et øget eksternt strålingsniveau og dels i en øget intern bestråling fra radioaktive isotoper, som optages i organismen med forurenede fødemidler. De øjeblikkelige problemer vil overvejende bestå i at beskytte mod det øgede strålingsniveau og den udvendige forurening af fødevarer, men på længere sigt vil den vigtigste kilde til fødemidlernes forurening være radioaktive stoffer, som fra forurenet jord optages i planterne og herfra eventuelt via husdyrene overføres til vore fødemidler. Afhandlingen omhandler alene problemer i forbindelse med radioaktivt strontium, fordi det er det fissionsprodukt, som på længere sigt må antages at kunne volde de største problemer. Indflydelsen af planteart, jordtype og forskellige dyrkningsmæssige faktorer er undersøgt med henblik på at vurdere betydningen af dyrkningsmæssige foranstaltninger til begrænsning af planternes strontiumoptagelse. I tilknytning hertil er der gennemført en mere detaljeret undersøgelse af, hvorledes kvælstofernæringen påvirker optagelsen og transporten af strontium og calcium i havre.

I kapitel 2 gives en kort omtale af de anvendte metoder, som er nærmere beskrevet i de originale afhandlinger. Dyrkningsforsøgene er gennemført dels som kar- og rammeforsøg og dels som vandkulturforsøg. Der er anvendt konventionelle metoder såvel til ekstraktion som til de kemiske og radiokemiske analyser. Den relative fordeling af strontium og calcium i forskellige faser af jord-plante systemet er angivet ved selektivitets- og fordelingskoefficienter, som beskriver om og i hvor høj grad, der diskrimineres mellem de to grundstoffer ved deres samtidige transport i systemet.

Kapitel 3 giver en oversigt over forskellige faktorers indflydelse på planternes optagelse af radioaktivt strontium fra kontamineret jord. En sammenligning mellem en række typiske danske jorde viste, at strontiumoptagelsen varierede med omtrent en faktor 10 med den mindste optagelse fra svære lerjorde og den største fra lette sandjorde med lavt pH. De jordbundsfaktorer, som især påvirker den relative optagelse af strontium og calcium, er arten og mængden af lermineraler og humusstoffer. I almindelighed har lermineralerne større affinitet til strontium end til calcium, medens der er en tendens til, at det er omvendt for humusstofferne. Den relative adsorption af de to kationer afhænger endvidere af koncentrationsforholdene, idet diskriminationen mellem dem synes at aftage med mætningsgraden.

Planternes optagelse af radioaktivt strontium kan til en vis grad reduceres ved tilførsel af stabilt strontium eller calcium på grund af ionkonkurrence. Men som følge af, at strontium adsorberes relativt stærkere end calcium ved en lav mætningsgrad, kan man få en stigende relativ tilgængelighed af strontium ved tilførsel af calcium og en mindre reduktion i planternes Sr/Ca forhold end den fortynding, der opnås i vandkultur. Ved den høje basemætningsgrad, der normalt findes i danske jorde, opnås kun en meget begrænset reduktion af strontiumoptagelsen ved tilførsel af kalk.

Derimod er det vist, at planternes optagelse af strontium kan reduceres betydeligt ved tilførsel af store mængder superphosphat (tabel 4), forudsat at der sikres en nær kontakt mellem de forurende jordlag og phosphatet (tabel 3). Antageligt dannes der tungtopløselige strontiumphosphater, som forårsager en reduktion af plantetilgængeligheden. Kombineres phosphattilførslen med en efterfølgende dybpløjning, der bringer det forurenede jordlag ned i ca. 40-50 cm dybde, kan der opnås en ikke ubetydelig reduktion i planternes optagelse af det radioaktive strontium. En endnu større reduktion vil kunne opnås ved at opvarme det forurende jordlag til temperaturer omkring 800^{o}C og derefter placere det under pløjelaget, men så drastiske forholdsregler kan formentlig ikke gennemføres for større områder.

Tilførsel af kaliumgødning har i nogle forsøg reduceret planternes optagelse af radioaktivt strontium, men virkningen har været ret begrænset og vil formentlig være uden praktisk betydning.

Der er en betydelig forskel mellem forskellige plantearters optagelse af radioaktivt strontium, og inden for samme planteart er der konstateret signifikante sorts-forskelle. Dette gælder således i amerikanske forsøg med hvede, byg og majs og i vore egne forsøg med bygsorter. Men også inden for plantearter og -sorter gælder, at der er et nært sammenhæng mellem indholdet af strontium og calcium, og det anses ikke for sandsynligt, at man ved forædling kan fremstille en sort, som diskriminerer væsentligt mere mod strontium, end der er normalt for arten.

Allerede i slutningen af forrige århundrede blev der gennemført undersøgelser (kap. 4), som tydede på, at strontium og calcium til en vis grad kunne erstatte hinanden i planteernæringen. Disse tidlige forsøgsresultater er stort set blevet bekræftet af de senere års undersøgelser. Men det er påvist, at de to stoffer ikke kan erstatte hinanden i alle metaboliske processer, og at strontium i højere grad end calcium fastlægges i tungtopløselige forbindelser i planterne.

Den relative optagelse og transport af strontium og calcium i planterne er afhængig af næringsstoftilførslen. Kapitel 5 giver en oversigt over en række undersøgelser til belysning af kvælstofernæringens indflydelse på optagelsen og transporten af strontium og calcium i havre. Det blev tidligt observeret (Ref. I), at kvælstoftilførsel øgede optagelsen af begge stoffer, men den relative fordeling blev også ændret, således at fordelingsfaktoren (DF), som vist i figur 2, aftog med stigende kvælstoftilførsel indtil omkring maximalt udbytte blev opnået. Det antages almindeligvis, at strontium og calcium kun transporteres fra rod mod top og kun i ringe omfang redistribueres i planterne. Resultater fra vandkulturforsøg (Ref. VII) bekræfter denne antagelse for strontiums vedkommende i havre, og det blev vist, at strontium, som aflejres i havrekerner, optages relativt sent i vækstperioden. Det må derfor forventes, at den relative fordeling i strå og kerne kan ændres som følge af en ændring gennem vækstperioden af den relative tilgængelighed af strontium og calcium. En belysning af kvælstofernæringens indflydelse må følgelig omfatte en undersøgelse af virkningen på strontium og calcium både før og efter de to kationer er optaget i planterødderne.

Forsøg med rajgræs tydede på, at ligevægtsreaktionen:

$$\text{Jord-Ca} + Sr^{++} \rightleftharpoons \text{Jord-Sr} + Ca^{++}$$

forløb mod højre gennem vækstperioden, idet Sr/Ca forholdet i afgrøderne aftog med tiden. Det blev endvidere vist i karforsøg med radioaktivt calcium, at den specifikke aktivitet i havrekernerne var lavere end i halmen. Begge disse resultater antyder, at det lavere Sr/Ca forhold i havrekerner end i havrehalm kunne skyldes ændringen i den relative tilgængelighed.

Men anvendelse af dobbeltmærkning (strontium-85 og calcium-45) viste tydeligt, at den relative tilgængelighed af de tilsatte radioaktive isotoper ikke ændredes med tiden, medens kvælstoftilførslen også i disse forsøg ændrede den relative fordeling af de to stoffer. På grundlag af disse forsøg konkluderes, at kvælstofvirkningen ikke skyldes ændringer i den relative tilgængelighed af strontium og calcium, men antageligt en indflydelse på selve optagelsen og transporten i planterne.

Kvælstofernæringens indflydelse på rodoptagelsen blev undersøgt i vandkulturforsøg med 2 uger gamle havre- og hvedeplanter (Ref. IX og X), medens transporten gennem stængler og translokationen til kernerne blev undersøgt i forsøg med afskårne havreplanter, som blev placeret i dobbeltmærket næringsopløsning i modningsperioden. Den relative optagelse af strontium og calcium afhang af Sr/Ca forholdet og Sr + Ca koncentrationen i næringsopløsningen. Ved anvendelse af opløsninger af lignende koncentration, som formodes at findes i jordvæsken, skete der en diskriminering mod calcium i forhold til strontium, idet Sr/Ca forholdet viste sig at være højere i rødderne end i næringsopløsningen. Ved translokationen i planterne skete der derimod en diskriminering mod strontium, således at Sr/Ca forholdet blev lavere i top end i rødder.

Ved vurderingen af rodoptagelsen skelnes mellem en fraktion, der er adsorberet til overflader i "apparent free space" i rødderne og en fraktion, som er absorberet i rodcellerne. Den adsorberede fraktion var forholdsvis uafhængig af kvælstoftilførslen, hvorimod den mængde, der blev absorberet, var stærkt afhængig både af kvælstof og af Sr + Ca koncentrationen. Forsøgsresultaterne tyder på, at diskriminationen mellem strontium og calcium mindskes ved stigende Sr + Ca koncentration og ved nitrattilførsel. Dette søges forklaret ved Epstein's (1966) teori om, at optagelsen formidles gennem to eller flere carrier, som har forskellig affinitet til strontium og calcium. Som alternativ forklaring anføres, at optagelsen kun delvis er formidlet af carrier mekanismen, medens en med kvælstofernæringen stigende del optages passivt med transpirationsstrømmen.

Transporten opad igennem ledningsstrengene i stænglerne foregår som en række kationbytningsreaktioner, hvor de negativt ladede positioner har større affinitet til strontium end til calcium, således at der ved transporten opad sker en vis diskrimination mod strontium. Denne diskrimination øgedes ved kvælstoftilførsel, således at Sr/Ca forholdet i toppen af velgødede havreplanter var lavere end i kvælstofmanglende planter. Translokationen af strontium og calcium fra blomsterstilkene til kerner var også afhængig af kvælstofernæringen. Forholdsvis mere calcium end strontium blev overført til kernerne, og denne forskel øgedes med stigende kvælstofforsyning (tabel 6). Denne virkning blev opnået både ved en rigelig kvælstofernæring i forbehandlingen og ved tilførsel af nitrat i den mærkede næringsopløsning. Det antages, at virkningen af forbehandlingen skyldes metaboliske processer, medens virkningen af nitrat i opløsningen skyldes en øget mobilitet på grund af den samtidige transport af an- og kationer.

Resultaterne fra vandkulturforsøgene støtter således de tidligere antagelser, der var baseret på karforsøg, at kvælstofernæringen påvirker planternes evne til at diskriminere mellem strontium og calcium. Den stimulering af strontium- og calciumoptagelsen, der sker ved kvælstoftilførsel, modvirkes af ændringen i diskriminationen, således at både strontium koncentrationen og Sr/Ca forholdet aftager i kernerne.

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ISBN 8755001777